IN SITU MATERIAL CHARACTERIZATION OF PAVEMENT-SUBGRADE SYSTEMS USING FWD DATA AND VALIDATION BY 3D-FE SIMULATIONS

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ABSTRACT

Nondestructive evaluation by deflection testing is widely used to assess the adequacy of existing airfield pavements, and strengthening design for future operations of aircraft applications. In situ modulus values of pavement layers were backcalculated using deflection data collected on airfield pavements for a marine airfield facility in Hawaii and Houston Intercontinental Airport. This paper also demonstrates the use of advanced three dimensional-finite element (3D-FE) dynamic analysis procedures for correctly simulating pavements subjected to falling weight deflectometer (FWD) dynamic loads. A comparison of simulated and measured FWD deflection time histories is made for asphalt pavement-subgrade systems. Linear elastic structural responses of 3D-FE pavement-subgrade models, subjected to aircraft wheel loads, are compared with the responses computed by the multilayered linear elastic analysis commonly used for mechanistic thickness design of airfield pavements.

A methodology has been developed for automatic discrimination of subgrade layering and generation of resilient modulus values of the subgrade layers using the Automatic Dynamic Cone Penetrometer (DCP) data files. The results have been validated by resilient modulus values measured in laboratory tests, and the FWD backcalculated modulus values. The subgrade modulus values have been verified using 3D-FE modeling and simulations.

INTRODUCTION

The structural response of an asphalt pavement is time- and temperature-dependent and affected by load-time history. Nonlinear modulus values for granular layers and soils associated with axle load configurations used in large modern aircrafts can reduce the backcalculated modulus values significantly. It is shown that the use of one set of design modulus values may be inadequate to assess pavement damage due to mixed aircraft traffic. Traditionally, highway and airport pavements have been modeled as static linear systems for structural response analysis. They are based on extrapolations of the full-scale loading tests, which relate pavement performance empirically with traffic repetitions and pavement responses calculated by linear static analysis. Accurate pavement response analysis, using appropriate material models, is imperative to develop appropriate performance models for mechanistic design of pavements. Most of the current pavement analysis procedures do not appropriately consider the effects of dynamic loading and pavement nonlinearity. The static analysis procedures ignore the effects of load-time history, pavement geometry, and thermal/moisture gradient on pavement responses. The two dimensional-finite element static analysis programs, exclusively developed for designing pavements, cannot simulate in situ states of stresses and strains in pavements subjected to FWD and heavy wheel loads (1). Many two dimensional-finite element pavements codes do not have the capabilities to combine all of the factors presented in pavement engineering, such as: discontinuities, nonlinearity, loss of support, cracking, temperature effects, etc. Limitations of these procedures and uncertainties in material properties may lead to incorrect structural response analysis of pavements.

The 3D-FE analysis enables the evaluation of the three dimensional state of stress and strain in a continuum by transforming the continuum into an assemblage of finite elements. The elements are interconnected at their common nodes. Some finite element codes, such as ABAQUS, DYNA3D, and LS-DYNA provide comprehensive 3D-FE static and dynamic analysis capability (1, 2, 3). The 3D-FE method allows for the dynamic analysis of pavements, and the consideration of finite or infinite dimensions of the physical pavement structure. It is equally important to recognize that appropriate and accurate material properties are essential for meaningful 3D-FE analysis. Advanced 3D-FE dynamic procedures are, therefore, important to implement for designing reliable and longer lasting pavements, which are recommended by the United States General Accounting Office (GAO) in a recent GAO report (4).

The deflections measured on a taxiway pavement for a marine airfield facility in Hawaii and a runway pavement at Houston Intercontinental Airport are presented in this paper. These values are used to backcalculate in situ modulus values of the pavement layers using the PEDD and UMPED computer programs, and are validated using 3D-FE simulation models.

MODULUS BACKCALCULATION METHODOLOGY BASED ON STATIC MULTILAYERED ELASTIC ANALYSIS

The structural analysis of a pavement-subgrade system subjected to FWD loading is generally evaluated using the static multilayered linear elastic theory. This approach assumes that the pavement-subgrade system behaves as a linearly elastic system. In the multilayered linear elastic model of pavement, each layer is characterized by its Young's modulus and Poisson's ratio. Each layer is assumed infinite in horizontal extent. The modulus backcalculation procedure involves an iterative application of the multilayered elastic theory.

The backcalculation methodology of the PEDD program has been formulated to determine the in situ moduli based on the best fit of measured deflections within reasonable tolerances. In this iterative procedure, a theoretical deflection basin is computed from the initial seed values of the moduli. Seed modulus values are calculated by the PEDD program using regression equations developed as functions of peak load, sensor distances from load, and input deflections (5,6). The first iteration is made to correct the subgrade modulus. Theoretical deflections are calculated. Correction is then applied to the modulus of the next upper layer, and theoretical deflections are calculated. This procedure is continued till the moduli of all layers are corrected and the error differences between measured and calculated deflections are reduced. Then another cycle of iterations is carried out again starting from the subgrade layer, if necessary, to reduce the errors.

The PEDD program has been enhanced by incorporating corrections in the FWD backcalculated modulus of subgrade and unbound granular layers for their nonlinear behavior (2). The UMPED program is a simplified version of the PEDD program, used for deflection data collected on asphalt or concrete pavements (7). The PEDD methodology has been extended to the FWDSOIL program to backcalculate the modulus of a subgrade and granular layer if FWD deflection data are collected on constructed subgrade and granular subbase/base layers (7).

BACKCALCULATION OF YOUNG'S MODULUS VALUES USING LS-DYNA

Since LS-DYNA calculates displacement history at every node in the model at a discrete set of times, we can use this data to compare with the measured FWD deflection time history. Therefore, this software can be used iteratively to verify the backcalculated modulus values and enhance these values using the FWD dynamic load pulse data. Highway pavement modulus values, backcalculated by the PEDD/UMPED programs, have been verified by 3D-FE simulations in previous studies (8, 9). In this study damping is ignored because the duration of the FWD load pulse is extremely short and does not affect the results of the analysis.

The 3D-FE models, presented in this study, are realistic representation of actual pavements to ensure accurate results and meaningful comparisons with the field measurements. The model geometry and finite element mesh used in pavement model studies at the University of Mississippi are based upon the classical work by Uddin et al (1, 2).

The FWD data on only one station out of 13 stations at Hawaii taxiway fillet section, selected randomly, was used for analysis. Similarly, only one station out of 150 stations of Houston runway section, selected randomly, was used for analysis. All other FWD data were not analyzed in this study because of limited time and scope of the simulation study.

Table 1. Pavement structure and backcalculated Young's moduli for taxiway fillet section (Station 100) at Kaneohe Marine Air Station, Hawaii (1996-97 study)

Backcalculation Method*	Backcalculated Modulus, MPa (ksi)				Subgrade + Depth to Rigid Layer m (in)**
	Asphalt Surface 101.6 mm (4 in)	Granular Subbase 609.6 mm (24 in)	Granular Subbase 609.6 mm (24 in)	Subgrade +	
MODULUS5 Static Analysis[a]	4,000 (580)	103 (15)	310 (45)	103 (15)	3.9 (152)[a]
PEDD Static Analysis[b]	4,572 (663)	119 (17.3)	119 (17.3)	121.8 (17.7)	12.2 (480)[b]
LS-DYNA Dynamic Analysis	4,572 (663)	119 (17.3)	119 (17.3)	121.8 (17.7)	12.2 (480)[b]

* Heavy FWD Data - 3rd Drop only (Peak force = 26,912 lbf)
** [a] With MODULUS5 rigid layer option; taken from the FWD test report (10)
** [b] PEDD analysis with an assumed rigid layer at 12.2 m (480 in), based on a previous parameteric study, to simulate the semi-infinite subgrade (1)
+ Subgrade depth (from the bottom of subbase to a rigid semi-infinite layer)

Taxiway Asphalt Pavement, Kaneohe, Hawaii

Table 1 shows the backcalculated moduli for the taxiway fillet pavement located at the Marine Air Station in Kaneohe, Hawaii which was tested by heavy FWD in late August 1996 during dry and hot weather (10). The water table was at 1.5 m (5 ft) below the pavement surface. Silty sand was found in the top 1 m (3 ft), followed by silty sand with gravel. The material below the asphalt layer was very similar, up to 4.5 m (15 ft), and the water table was at 0.6 m (1.8 ft).

Therefore, similar modulus values are expected for the granular base, subbase, and subgrade layers, which is evident from the boring records.

The results of the MODULUS5 backcalculation program, shown in the first row of Table 1, indicate a low subgrade modulus which is expected because of the relatively smaller subgrade thickness over the "rigid" bottom predicted by the program which also resulted in an unreasonably high modulus of the subbase layer. The results may be different if a larger subgrade thickness of 12.2 m (480 in) is assumed in the MODULUS5 analysis. The PEDD backcalculation is based on an assumed subgrade thickness of 12.2 m (480 in). The PEDD backcalculated modulus values are more reasonably accurate because the modulus values of granular base, subbase and subgrade are more representative of a relatively homogenous sandy silt material, as indicated by the boring data. The backcalculated values obtained from the PEDD static analysis were used as material properties for the 3D-FE Half-Model shown in Figure 1(a). Figure 1(b) shows the deformed model at the time of peak deflection. Figure 2 compares the measured FWD deflection with the PEDD deflections and peak LS-DYNA deflections. The results agree reasonably, and therefore, the PEDD backcalculated modulus values are verified by the 3D-FE dynamic analysis.

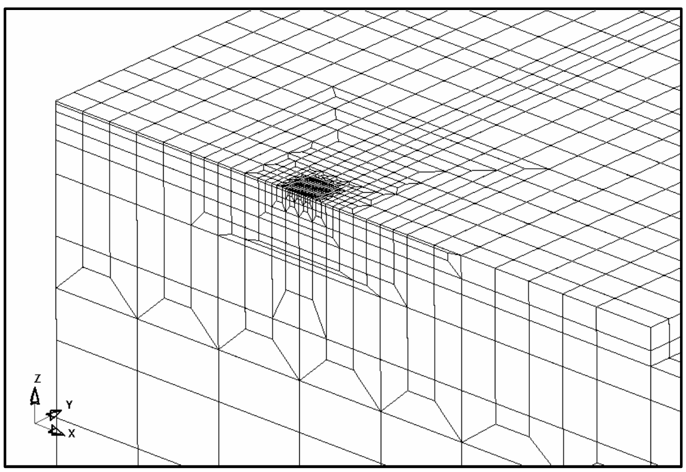


Figure 1(a). 3D-FE Half-Model for taxiway fillet at Kaneohe Marine Air Station, Hawaii, before applying FWD pulse load

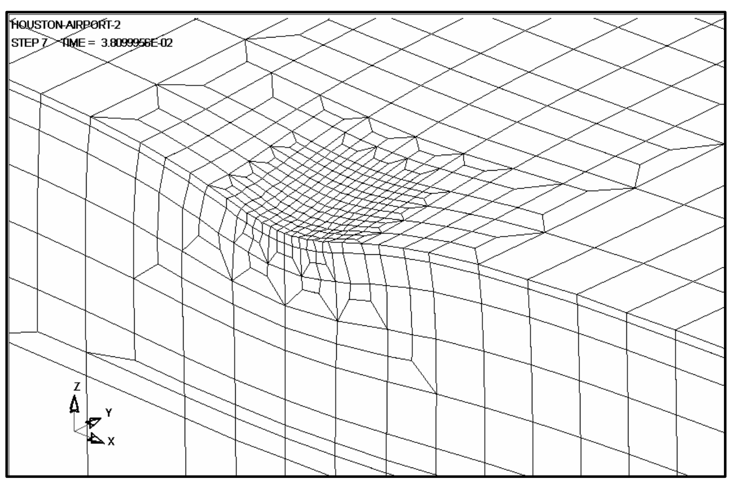


Figure 1(b). 3D-FE Half-Model for taxiway fillet at Kaneohe Marine Air Station, Hawaii, deformed model at FWD load time = 0.038 sec

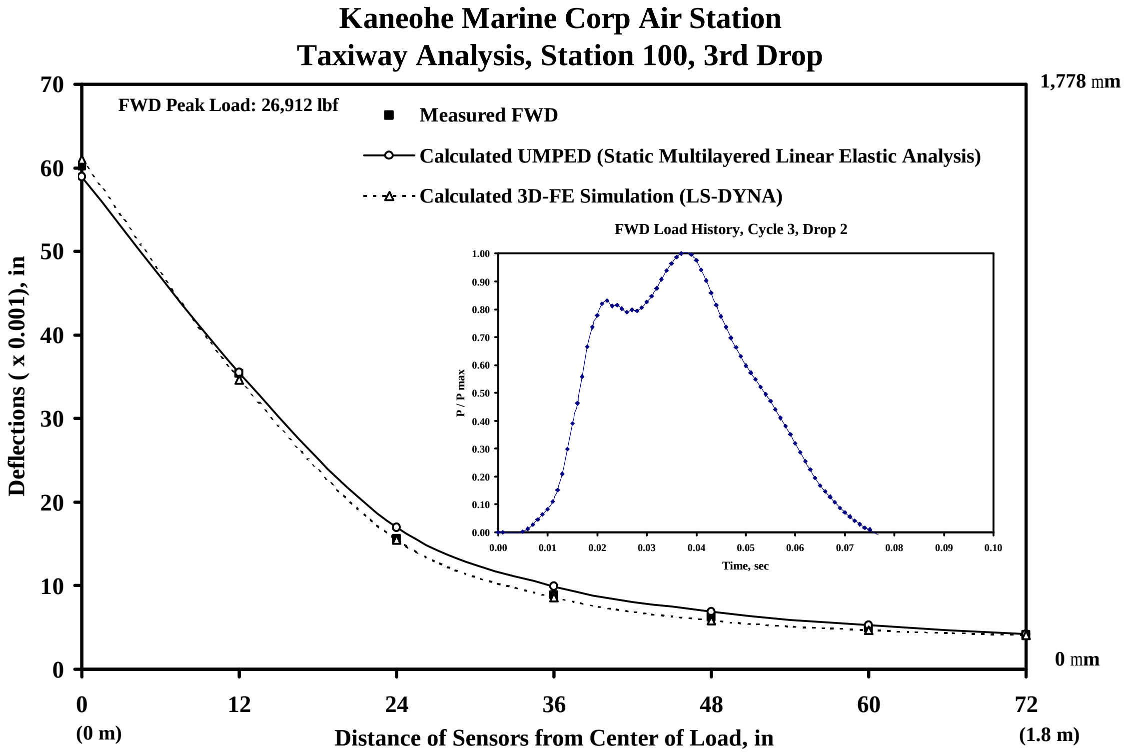


Figure 2. Comparison of the deflection basin for the taxiway fillet at Kaneohe Marine Air Station, Hawaii

Runway Asphalt Pavement, Houston Intercontinental Airport

The deflection data from heavy weight deflectometer (HWD) tests were conducted on Runway 9-27 at Houston Intercontinental Airport. The runway pavement section consisted of four layers. Table 2 shows the thickness for each pavement layer. These thicknesses were obtained from the results of the cores and the laboratory data (11). These data were used to balckcalculate in situ modulus values.

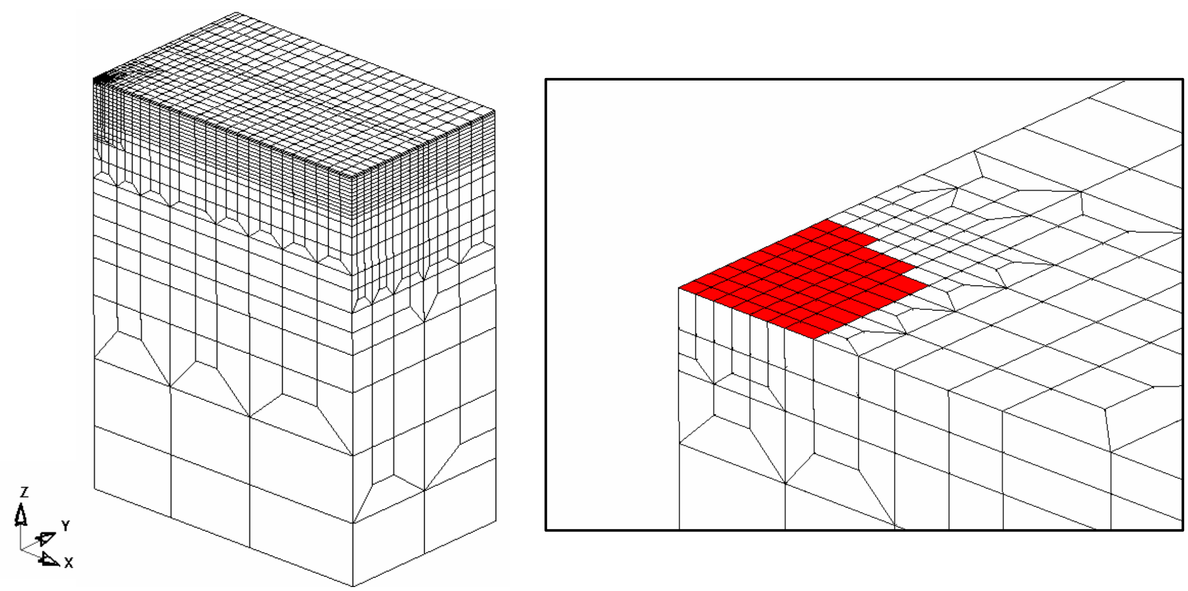
From the HWD data, and using the UMPED computer program, the in situ modulus values were backcalculated, as shown in Table 2. The subgrade modulus seems relatively higher, however, it is not unreasonable considering very small vertical strain on the subgrade because of the thick strong pavement layers. This observation is discussed by Uddin et al in their pioneering work of applying the equivalent linear analysis approach for nonlinear analysis of modulus values of pavement granular base and subgrade soils (5, 6). The backcalculated modulus values shown in Table 2 were used as the material properties for the 3D-FE simulations.

Since the commonly used width of a runway is 45.72 m (150 ft) and the computer time for dynamic analysis is a concern, the 3D-FE simulation model chosen for this study was the Quarter-Model. The responses under the FWD load, such as strains and stresses, attenuate with distance away from the load area and become almost zero. Therefore, the 3D-FE model can be reduced in size without considering the entire pavement model. The use of a 3D-FE Quarter-

Model for highway pavements has been reported and evaluated in a recent study at the University of Mississippi (8). The HWD set of deflections used for the Houston runway study was the first drop data at a peak load of 9,803 kgf (21,612 lbf). Figure 3(a) shows the 3D-FE Quarter-Model used for the runway pavement analysis. The 3D-FE Quarter-Model contains 10,955 nodes and 9,544 elements. The boundary conditions used in this 3D-FE model are fixed at the bottom and roller supports (free movement in vertical direction) on the XZ and YZ planes. The HWD load area of 401.3 sq. cm. (62.2 sq. in.) is shown in Figure 3(b). A pressure of 599 kPa (86.9 psi) is applied on the darkened region used for the FWD load.

Table 2. Houston Intercontinental Airport, Runway 9-27

Layer	Material	Thickness mm (in)	Backcalculated Modulus, MPa (ksi)	Poisson's Ratio	Mass Density kg-sec^2 / m^4 (lb-sec^2 / in^4)
1	Asphalt	101.6 (4.0)	4,774 (692.3)	0.35	2.5060E+02 (2.3000E-04)
2	LCFA Base	723.9 (28.5)	8,963 (1,299.6)	0.30	2.2280E+02 (2.1000E-04)
3	CTB	863.6 (34.0)	620 (89.9)	0.30	2.0380E+02 (1.8700E-04)
4	Subgrade	12,192 (480)	393 (56.96)	0.45	1.8870E+02 (1.7320E-04)



(a) 3D-FE model (b) Refined mesh at HWD load area

Figure 3. 3D-FE Quarter-Model for Runway 9-27 at Houston Intercontinental Airport

Figure 4 compares the results of this 3D-FE simulation model with the measured deflections and the deflection calculated by the UMPED program. The measured deflections are relatively low because of thick and strong pavement layers, however, these data are within the accuracy limits of the HWD geophanes. The peak deflections obtained from the 3D-FE model are generally smaller than the deflections from the HWD test and the UMPED program. The maximum error of 11% obtained from the 3D-FE simulation model with the HWD measured deflections is acceptable. Figure 5 shows a snapshot of the 3D-FE Quarter-Model deformed under the HWD load pulse at the time of maximum deflection (step 9, time = 0.047 sec).

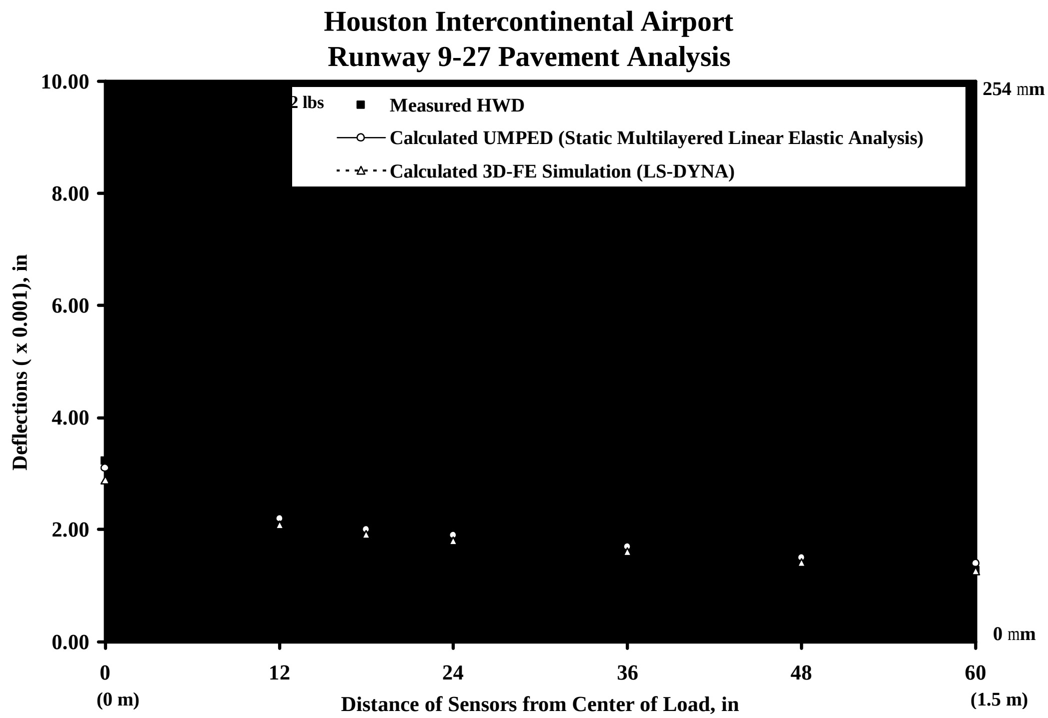


Figure 4. Comparison of the deflection basin for Runway 9-27, Houston Intercontinental Airport

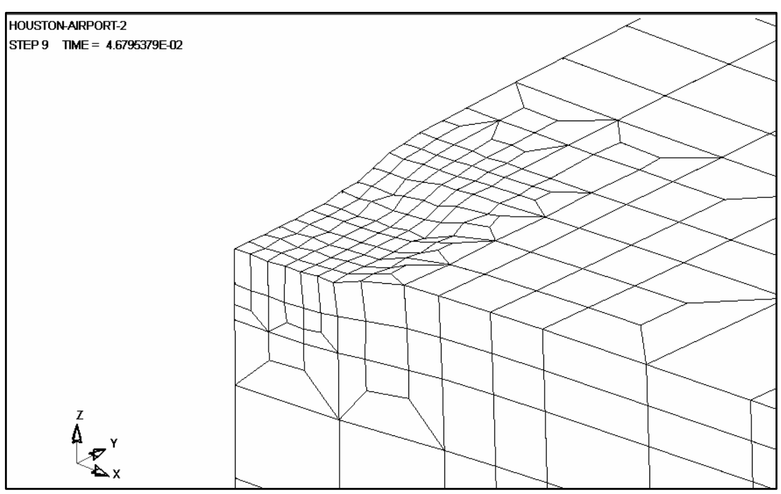


Figure 5. 3D-FE Quarter-Model maximum deflection at Time Step = 0.047 sec

PAVEMENT STRUCTURAL RESPONSE ANALYSIS CONSIDERING NEW GENERATION AIRCRAFT

In 1958, the 159 ton DC-8 was the most critical aircraft in the world's commercial fleet with respect to pavement design. Since that time, manufactures have been developing new larger aircraft with more wheels and/or greater spacing between wheels (12). The Boeing 777 aircraft, a recently marketed heavier aircraft, with a maximum weight of 317,514 kgs (700,000 lbs) and a new landing gear configuration, includes the use of the new triple-axle. Existing methods of airport pavement designs are inadequate to compute damage caused by the B777 aircraft and by other very large multiwheeled, multigeared aircraft, such as A-3XX series of Airbus.

Recently, it has been announced that the Airbus A-380 aircraft will have a maximum weight of 544,310 kgs (1,200,000 lbs). The landing gear configuration for this aircraft includes two tandem-axle and two triple-axle, with a total of 20 tires (13). The approximate weight per tire will be around 27,216 kgs (60,000 lbs). The effect of this new loaded aircraft on existing pavement sections will be an increase in the stresses and strains in the pavement layers and a possible reduction in the performance and life of the pavement. The need to evaluate and verify actual airfield pavement sections for supporting this new generation aircraft load is obvious. The evaluation and validation of the structural response of actual airfield pavement, using appropriate values of Young's modulus and 3D-FE simulation models, is desirable.

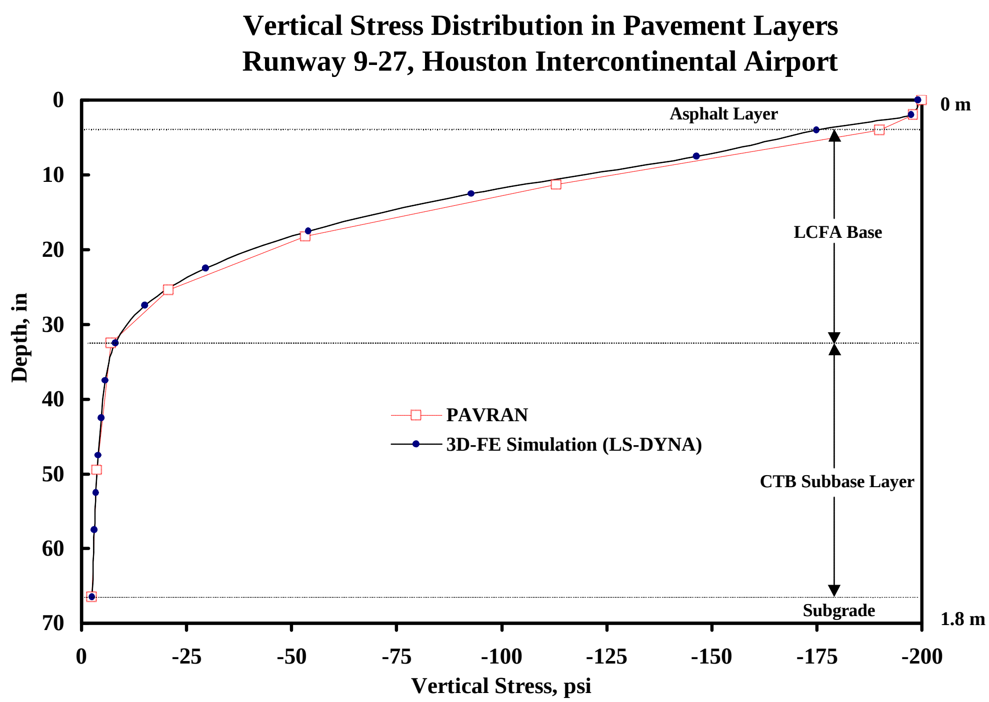


Figure 6. Vertical stress distribution on pavement layers for Runway 9-27, Houston Intercontinental Airport

Figure 6 shows a comparison of the peak vertical stresses obtained from the 3D-FE analysis of the Houston Intercontinental Airport Quarter-Model and the stresses obtained using the

PAVRAN (PAVement structural Response ANalysis) computer program. The load utilized in this comparison is the A-380 wheel load of 27,216 kgf (60,000 lbs) with a tire pressure of 1,379 kPa (200 psi). The plot shows that the vertical stresses calculated by the PAVRAN multilayer elastic analysis for a thick and strong pavement section reasonably agree with the peak vertical stresses computed from the 3D-FE pavement model. Further comparisons for weaker pavement sections are in progress.

FWD AND DCP TESTING ON CONSTRUCTED SUBGRADE AND 3D-FE SIMULATIONS

In this section, backcalculated modulus values for compacted subgrade layers using the FWDSOIL program are evaluated using 3D-FE simulations. Table 3 shows the subgrade layers for US45N Section 2 South Project (Station 111+50) after the construction of subgrade and moduli backcalculated by the FWDSOIL program (7, 8). The subgrade layer thicknesses were automatically calculated from the DCP test data by using the newly developed DCPAN software (7, 8). This approach allowed realistic modeling of the subgrade soil layers. For this compacted subgrade section, the smallest peak FWD load (Drop 1) results were used for backcalculation.

Most of the pavement analysis programs assume a pseudostatic load for FWD deflection tests (5). On the other hand, the LS-DYNA code generates dynamic deflection time histories by subjecting the pavement model to the FWD dynamic load pulse. Therefore, the modulus values backcalculated assuming a pseudostatic load were used in the LS-DYNA dynamic analysis to verify the accuracy of the backcalcuated modulus values. Figure 7 shows a comparison of the shapes of the measured and calculated deflection basins under the FWD load. The four curves are: (a) peak deflections from FWD sensors measurements, (b) calculation by the FWDSOIL static analysis program, and (c) the LS-DYNA peak deflection results using different subgrade Layer 1 Young's modulus values. A better match of the deflection basin is achieved by reducing the Young's modulus of subgrade layer 1 by 22 percent, as shown in Table 3. However, the modulus values of the second layer and the last subgrade layer remain unchanged, the same as backcalculated by the FWDSOIL program. The modulus values of subgrade layer 3 is more representative of the design subgrade modulus. The top 152.4mm (6 in) subgrade soil (layer 1) was later treated with lime, therefore, the modulus of this layer is expected to change.

Table 3. Comparison of backcalculated Young's modulus values, US45N Section 2, South Project, Station 111+50, Monroe County, Mississippi

Subgrade Layer	Thickness Mm (in) from DCP tests	Young's Modulus MPa (psi)		
		FWDSOIL	LS-DYNA 1	LS-DYNA 2
Layer 1	152.4 (6)	160.7 (23,300)	160.7 (23,300)	124.1 (18,000)
Layer 2	228.6 (8)	9.7 (1,400)	9.7 (1,400)	9.7 (1,400)
Layer 3	12,877.2 (507)	46.6 (6,760)	46.6 (6,760)	46.6 (6,760)

LS-DYNA 1: Original 3D-FE dynamic analysis using Young's Modulus backcalculated by FWDSOIL.
LS-DYNA 2: 3D-FE dynamic analysis with the reduced value of Layer 1 Young's Modulus.

Deformation of US45 Section 2 ST111+50 Subgrade

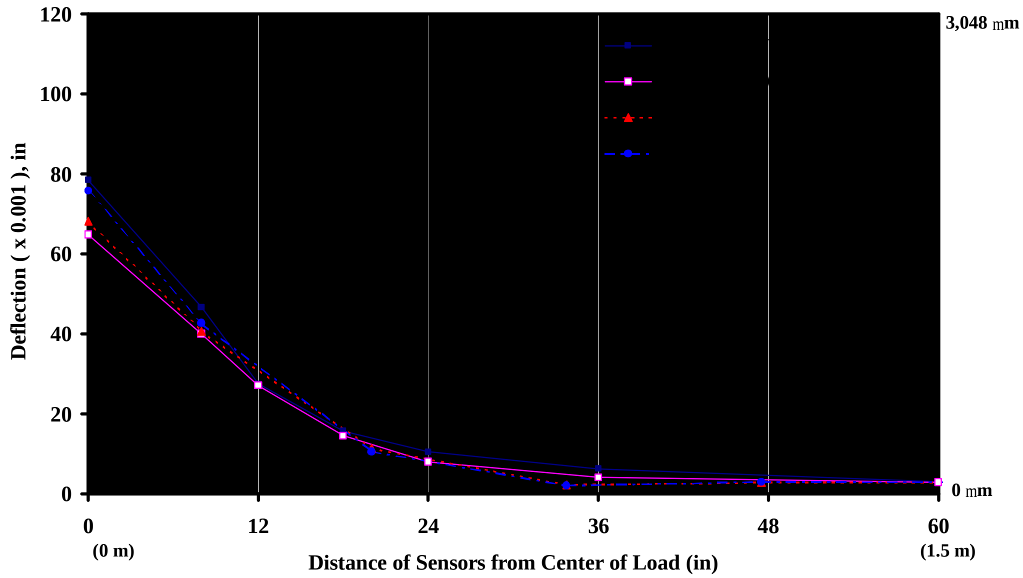


Figure 7. Comparison of the deflection basins normalized by 5,000 lbs

Deflection Time History under FWD Loading Plate
US45N Section 1, ST 464+05, Cycle 2, Drop 1 and Drop 2

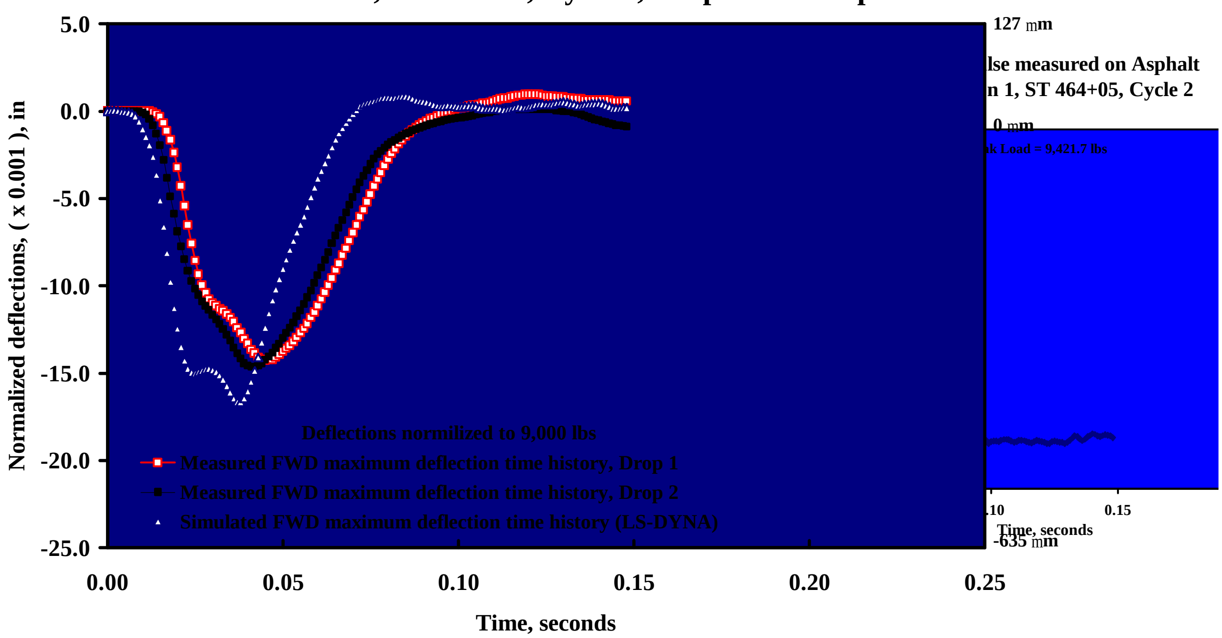


Figure 8. Simulated and measured FWD maximum deflection time history plots

Figure 8 shows the simulated and measured FWD deflection time histories for another section after 152.4mm (6 in) lime-treatment, 152.4mm (6 in) stabilized base, and 76.2 mm (6 in) over the subgrade test section (Station 464+05). The simulated FWD deflection time history was obtained using the 3D-FE model and the maximum deflection at the center of the loading plate. The measured FWD deflection time history was extracted from the falling weight deflectometer data file. The shapes of the measure deflection history and deflection history calculated from the 3D-FE model are reasonable but not in perfect agreement. The measured load-time history is also shown in Figure 8 which is similar in shape as the simulated deflection history shape. Further simulations of deflection-time history data are currently underway. Recall that in earlier studies, the average modulus values backcalculated using the PEDD/UMPED programs were validated by 3D-FE modeling and simulation for asphalt pavements (8, 9).

SUMMARY AND CONCLUSIONS

It is recognized that the modulus backcalculation methods using FWD dynamic deflection data are based on the static multilayered linear elastic theory. Therefore, it is necessary to verify the backcalculated Young's modulus values by conducting three dimensional-finite element dynamic analysis. The 3D-FE method allows for the dynamic analysis of pavements and the considerations of finite or infinite dimensions of the physical pavement structure. This paper presents the development of 3D-FE models using the LS-DYNA simulation software.

In this study, two different 3D-FE asphalt pavement models have been created; (a) a Half-Model for taxiway fillet (Station 100, Kaneohe Marine Air Station, Hawaii) and (b) a Quarter-Model for Runway 9-27 (Houston Intercontinental Airport). The falling weight deflectometer and heavy weight deflectometer tests conducted on these two pavements were analyzed to backcalculate in situ modulus values. The in situ modulus values backcalculated from the deflection and layer thickness data and the PEDD/UMPED backcalculation programs were used for 3D-FE simulations. The deflection results calculated from the 3D-FE dynamic analysis agree reasonably with the deflections measured by the FWD and HWD devices. Therefore, the 3D-FE models presented in this paper verify the modulus values backcalculated by the PEDD/UMPED computer program. The 3D-FE runway pavement model was used to study the dynamic structural response subjected to the aircraft wheel load. The vertical stress distribution from the multilayered linear elastic analysis agrees with the results of the 3D-FE simulations.

The FWDSOIL backcalculated modulus values on a constructed subgrade section have been verified by 3D-FE simulations. A comparison between simulated and measured FWD deflection time histories is shown. The 3D-FE modeling and simulation is a powerful tool that could help pavement engineers and investigators to accurately analyze real airfield pavement problems and enhance the interpretation of FWD load-time history data.

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